Comparing Soft Actuators for Enhancing MRI Pituitary Tumor Detection

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Abstract

The pituitary gland is a small gland at the base of the brain and above the nasal passages. It releases hormones that control the levels of hormones produced by most other endocrine glands in the body. Tumors on this gland can lead to adverse health effects by causing an excess release of hormones and some can be cancerous. In addition, if the tumor becomes larger than about a centimeter, it can grow to compress and damage nearby parts of the brain.

Currently, MRI scans are considered to be the best way to detect pituitary tumors, but machines sometimes lack the detail to detect smaller tumors. One way to improve the imaging is to obtain a local image with a coil in close proximity to the desired viewing area to obtain. In this paper, we focus on using soft robotics techniques and materials to design a fixture that can safely enter the human body while in an MRI machine and insert a coil near the pituitary tumor via the nasal cavity. Beyond enhanced detection of pituitary tumors, this research has an impact on applying soft robotics to surgeries and medical procedures.

Introduction

The pituitary gland is a small gland found at the base of the brain and above the nasal passages [1]. It releases hormones that control the levels of hormones produced by most other endocrine glands in the body [2] [3]. Tumors on this gland can lead to adverse health effects by causing an excess release of hormones and some can be cancerous [1] [2] [3]. In addition, if the tumor becomes larger than about a centimeter, it can grow to compress and damage nearby parts of the brain [1].

Currently, MRI scans are considered to be the best way to detect pituitary tumors, but machines sometimes lack the detail to detect smaller tumors [3]. One way to improve the imaging is to obtain a local image with a coil in close proximity to the desired viewing area [4] [5]. For the purpose of viewing the pituitary gland, the sphenoid sinus is a suitable area. In this paper, we take on the challenge of finding a material to place such a coil in the sphenoid sinus. To do so, we look at two different engineering materials as candidates for a fixture to place such a coil. The materials are shape memory polymers (SMPs) and pneumatic actuators (PNAs).

Shape memory polymers are smart materials with the ability to undergo a large recoverable deformation upon the application of an external stimulus [6] [7]. These stimuli include heat, light, magnetic fields, electricity, water, and pH value [6] [7] [8]. SMP can also be actuated using composite materials such as magnetic nanoparticles or carbon nanotubes (CNTs) to activate its stimulus [8] [9] [10]. Most of these methods require direct contact or, in the case of light. a direct line of sight to stimulate the SMP. This may prove to be difficult while inside the nasal cavity or the body in general. Magnetic and or metal materials would interfere with the MRI. Due to these constraints, indirect heating with carbon nanotubes was found to be among the most viable means of actuation. Passive heating from body temperature is also explored.

Pneumatic actuators are a soft robotic concept that use embedded pneumatic networks of channels in elastomers that inflate like balloons for actuation [11] [12]. Many papers use PNAs as grippers or bioinspired soft robots [11] [13] [14] [15]. However, there is recognition for their possible biomedical and healthcare applications [12]. This paper takes a look at using PNAs and SMPs as possible materials for a medical tool to place a coil in close proximity to the pituitary gland.

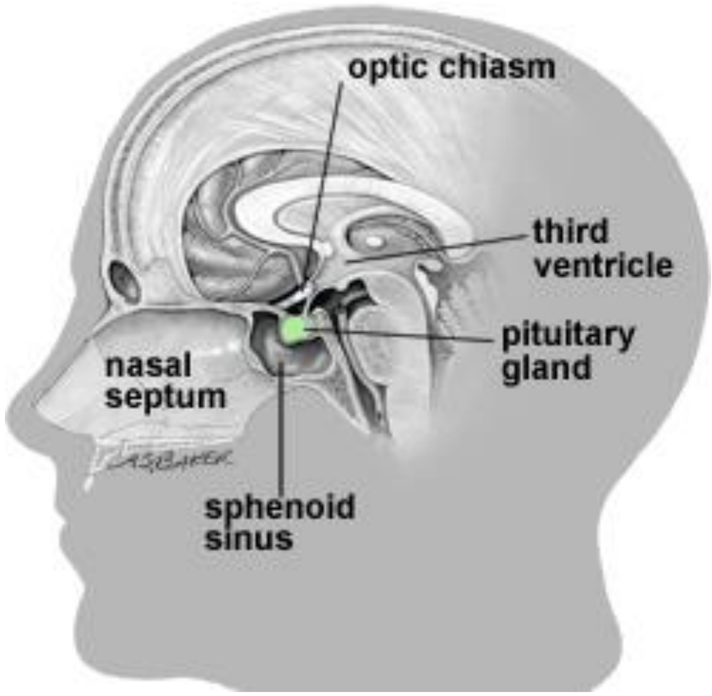

Figure 1: Shows the relative location of the sphenoid sinus and pituitary gland.

Methods

Material Fabrication

3D Printed SMP

The idea for the passive 3D printed SMP is derived by Wu and colleagues, 2016 [16]. The procedure utilized in this study closely follows Wu's method to replicate one of the SMPs which consists of a matrix made of Tangoblack+ (Tg~2 °C) and two fibers made of DM8530 (Tg~57 °C) and DM9895 (Tg~38 °C). All are digital materials from the Stratasys digital library and were printed using the Object 350 3D printer. The original design is a 70 mm long, 6 mm wide, and 2 mm thick strip with the fiber dimensions 70 mm long, .38 mm wide, and .38 mm.

For the scaled down model, the shape of the original model is modified. It is shrunk to a 70 by 2.5 by 2.5 mm rectangular block and the edges are rounded. The size of fibers 1 and 2 remain 70 by .38 by .38 mm, but the number of fibers is reduced to 4 of each.

To program the shapes, both models are heated at a temperature T_H = 70 °C and stretched to 10% strain. They were then cooled to about 0 °C while still held in the strained position.

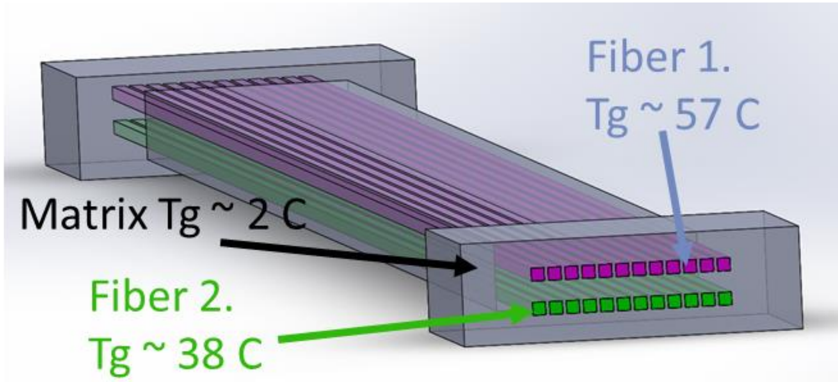

Figure 2: CAD model of the 3D printed SMP

Pneumatic Actuator

The idea for the pneumatic actuator came from Wakimoto et. al, 2009 [14]. The paper produced miniature pneumatic actuators. A 13 cm long, 9 mm radius, semicircle actuator with half bellows is replicated using different techniques from the original paper. The macro sized actuator uses a slightly different form of silicon from the original paper. The silicon is a two-part solution called Dragon Skin30 that starts to cure once mixed. The silicon is shaped using a 3D printed mold and degassed before being left to cure. Afterward, a thin flat layer is cure to the bottom of the mold to close the actuator. The smaller sized replica is made using the same process. The mold is exactly the same as the mold for the macro sized actuator, but scaled down to 34 mm long and 2.25 mm radius.

Figure 3: Pneumatic actuator after demolding

*SMP/CNT Composite***

The concept of a SMP/CNT composite came from Leng and colleagues, 2014 [10]. This SMP is a two-part (A&B) solution with a pot life of 210 seconds from SMP Technologies. Four models with different concentrations (0 wt%, 1 wt%, 3 wt%, 5 wt%) of CNTs were synthesized on a macro scale. Because the pot life is so short, the CNTs are thoroughly mixed into one of the solutions before they are combined.

Experimental Design

Three materials (a passive SMP 3D printed from digital materials, an SMP/CNT Composite, and a beveled PNA) are tested on their ability to make it safely to the sphenoid sinus in a custom 3D printed model. The file for the anatomical model was provided by ZYGOTE (USA). Each material is tested on a macro scale for proof of concept, before being scaled down to a size suitable to traverse the human nasal cavity.

After being scaled down, each material is tested on its ability to successfully enter the nostrils of our 3D printed model and make its way to the sphenoid sinus. The 3D model is printed with a soft material to simulate the elasticity and softness of the tissue and cartilage in the nasal structures. It also has external constraints to simulate the bone around the structures.

In addition to the ability to successfully reach the sphenoid sinus, we look at the hardness and toxicity of each material, test the load capacity if each material, and test different characteristics of each material based on its properties. The curvature over time is measured for the 3D printed SMP. The relationship between curvature and pressure will be measured for the pneumatic actuator. The upper heat capacity, and relationship of curvature and microwave frequency will be measured for the SMP/CNT composite.

**Due to time constraints, the SMP/CNT Composite was not fabricated and tested. The test in the model of the nasal structure was also unable to be performed because the model did not come with dimensions. Dimensions of the sphenoid sinus were found. They will help scale the model proportionately, due to lack of time, the model was not printed to scale.

Results

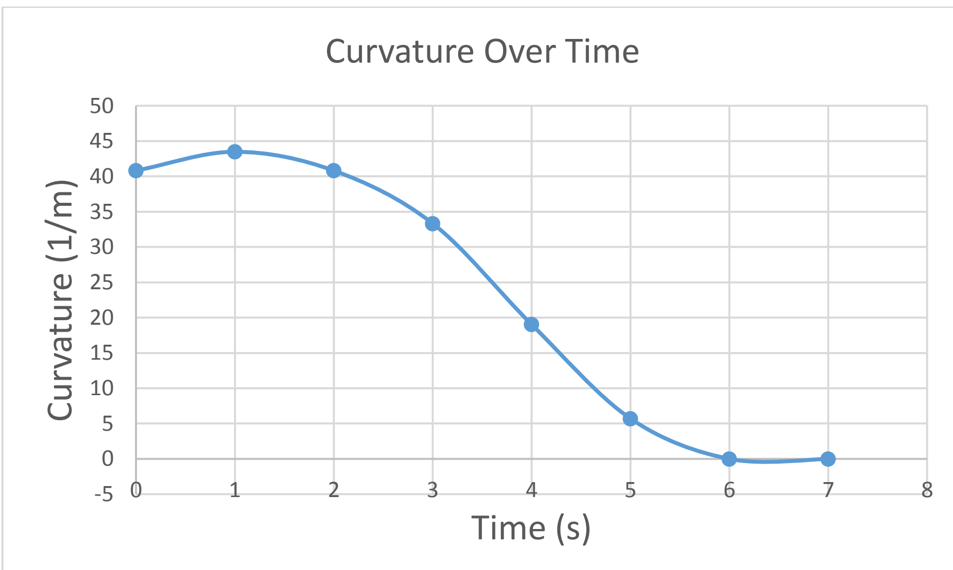

Figure 4: Graph of curvature vs. time for 3D Printed SMP

Both the micro model and proof of concept model of the 3D printed SMP behaved in the same manner. The 3D printed SMPs begin to immediately start its memory shape behavior in room temperature (24-27 C) after being programmed. It reaches near its maximum curvature in less than a minute. The data from figure 4 is taken from placing the SMP in a hot water bath about one minute after programming. Once the entire actuation process is completed, no further actuation can be achieved without reprogramming.

The proof of concept model, which weighs 1.2 grams, underwent large, immediate deformation when carrying a load of 1.02 grams and creeping deformation carrying a load of 0.2 grams. The actuator also is stiff outside the field of actuation.

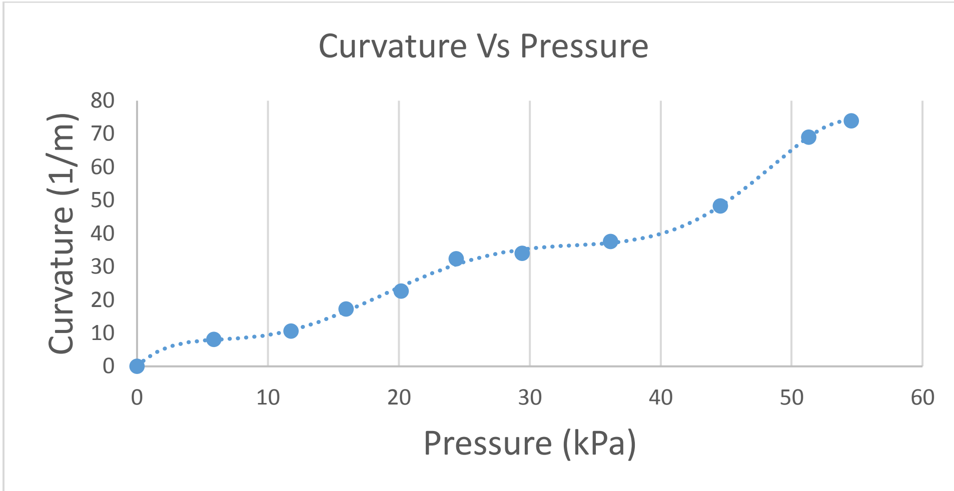

Figure 5: Graph of curvature vs. pressure for Pneumatic Actuator with electric pump as pressure source.

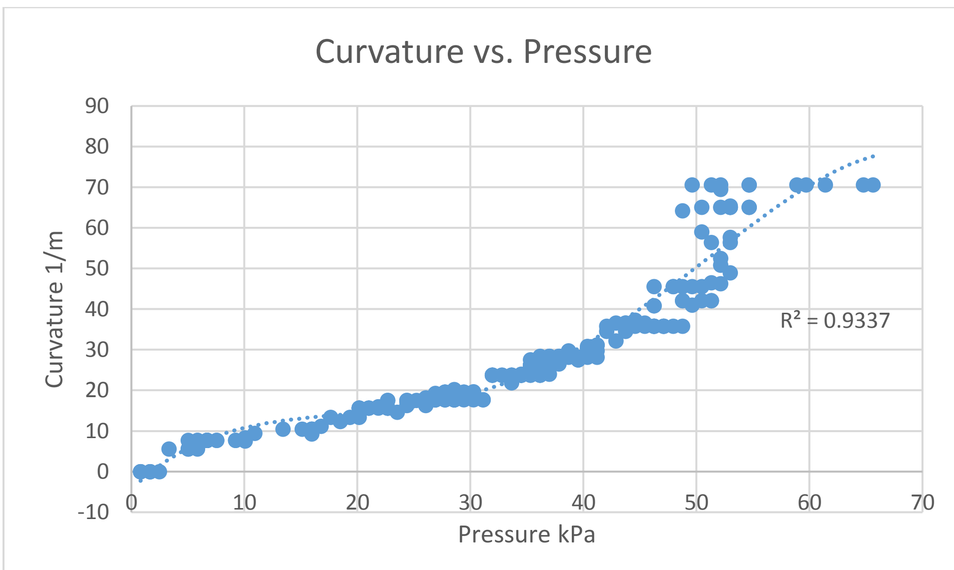

Figure 6: Graph of curvature vs pressure with 30 mL syringe as pressure source.

Only one of the pneumatic actuator models was successful. The miniature model scaled down to fit into the nasal structure proved to be difficult fabricate. The figures above show the larger model's curvature as a function of pressure. Curvature was measured by treating the actuators as arcs on a circle and using the formula h/2 + c^2/(8h), where c is the length of the chord and h is the distance from the center of the chord to the center of the arc. Figure 5 comes from a short video with the pneumatic actuator controlled by an electric pump. Figure 6 comes from a longer video with the actuator being controlled by a syringe. Both show a nonlinear increase of curvature with an increase in pressure. The pneumatic actuator carried a load of roughly 0.7 grams with little deformation. It was able to withstand 152 kPa of pressure before the actuator failed.

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Table 1: Summary of Properties and Measurements of Models

Material	Peak Curvature	Tg (C)	Load carried without large deformation	Hardness	Toxic	Pressure at failure	Max heat Requirement (C)
3D SMP	43	F1~57 F2~38 M~2	0.2 g	Shore D 82 Shore A 95 Shore A 28	No	NA	70
PNA	~70	NA	~0.7 g	Shore A 30	No	~152 kPa	NA

Discussion

Shape memory alloys, SMPs with magnetic nanoparticles composites, and SMPs coated with a light absorbing CNT film were also briefly looked at as a potential material for our task. Shape memory alloys and magnetic SMP composites were dismissed as possibilities because they would interfere with the images taken by the MRI machine. The light actuated SMPs had seemed viable, but they would require a direct line of sight for the light [19] [20]. This could be accomplished by adding a light emitting catheter, but the coating may require heating that would burn tissue to achieve actuation [19]. An insulating silicon material could be used to insulate this heat, but it could hinder actuation. PNAs and the 3D printed SMP seem to be the best available solutions at the time.

Since the actuation of the 3D printed SMP is passive and dependent on time and ambient temperature, using it for a biomedical procedure would require the operator to master a timed precision technique. This would make the operator the conform to the actuator's properties, rather than giving them control over the actuator. The actuator also completes the same actuation sequence every time it is reprogrammed. Because the actuation depends on stress and strain differences between the three materials of the actuator, the actuation can be changed based on the geometry of the fibers in the matrix. However, the actuation will always follow the same set pattern and has to be reprogramed each time actuation is achieved.

The complete actuation pattern also requires an excessive amount of heat (~57 Celsius) that surpasses the body temperature that could damage tissue and have other harmful symptoms to the body [21], but room temperature is adequate to achieve the enough bending to perform a 90 degree turn. However, the actuator begins to return to its programmed position when slightly above body temperature. This could be a problem with a patient who has a slight fever or body temperature has risen for some other reason.

Also, the actuation force is very low. This places a tight weight constraint on the coil and any other possible attachments such as a camera. The attachments would have to be designed to avoid an overbearing load that would overcome the actuation force leaving the actuator to behave poorly.

The PNA is difficult to fabricate due to its complex shape. The model used for testing was flawed because air bubbles were trapped in the silicon as it cured. Earlier trials of this model were unsuccessful due to the mold inhibiting the silicon from completely curing. These problems were more detrimental for miniature model. A better process for fabrication would entail a mold that allows degassing over wider area and a mold capable of withstanding high heat to decrease cure time.

The PNA provides easy control through air pressure and has a more flexible range of motion than the 3D printed SMP. It also has multidirectional actuation as opposed to the passive, one directional motion of the 3D SMP. The actuation force is greater than that of the 3D SMP, but the comparison would not be sound because the actuators are dissimilar in size.

Conclusion and Future Work

Between these two actuators, the pneumatic actuator seems to be the most viable option mainly due to its active actuation. Since there have been difficulties in the fabrication process using the 3D printed mold, the mold should be redesigned or another type of mold should be used.

Both materials should be tested more at a size intended for application. The actuation for both materials should be characterized under load conditions and the curvature should be measured using a more accurate representation of the. Once the nasal model is set to the proper scale, the actuators should be tested to make sure they would be able to maneuver through the cavities.

Future work for this project requires knowledge from various backgrounds. Things that need to be accomplished include the characterization of the cartilage in the nose, the nasal mucosa, and other tissue in the form of Shore Hardness so they can be compared to elastic materials and Young's Modulus so they can be compared to inelastic materials. Materials that mimic the cartilage and tissues are need to create an accurate model of the nasal cavity and sinuses. Other biomechanical properties of the area of interest such as the ambient temperature, moisture content, and safe temperature range also need to be found so that the models can be accurate environmentally as well as anatomically. The CNT/SMP composite should also be revisited as an option once a kit for a softer SMP is made available. Lastly, a coil that expands once it reaches its destination and contracts when traversing the nasal cavities would be beneficial because the image of the local area increases with the coil's area.

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